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1. INTRODUCTION

Platform attitude is a key quantity necessary for interpretation of most airborne measurements. Wind calculations require fast, accurate measurements of roll, pitch, and heading. Likewise, radiometric, photographic, lidar, and radar remote sensing applications require platform attitude to determine the pointing direction of the sensor for geographic rectification of their data.

Until recently, attitude determination required the use of inertial reference systems (IRS). Early IRSs consisted of mechanical-spun gyros. These were extremely accurate, but did not have a high MTBF and typically required a lot of maintenance. These were later replaced by Laser Ring Gyros and Fiber Optic Gyros for all but the most demanding applications in terms of accuracy. These newer gyros somewhat reduced size and cost while significantly reducing the gyro failure rate. Even more recently, miniature, less expensive piezoelectric rate-gyro based IRSs have been introduced that look promising for future use in light aircraft applications, where the availability of space impose severe size and weight restrictions and long term accuracy is not important. In addition to IRSs, advancement in Global Positioning technology has made it possible to determine platform attitude using a system consisting of four GPS receivers, with a common clock or local oscillator, operating from an array of four antennae in a known configuration. The four receivers are generally packaged together in one enclosure and the data from the four is processed into platform attitude by a single central processor. These GPS attitude systems determine attitude without measurements from gyros or accelerometers, using only the geometry between each satellite and the antenna array. Such systems are currently or have been utilized on several small and large aircraft alike for

atmospheric research (e.g. LongEZ operated by NOAA/ARL, PNNL Gulfstream-1, ARA Grob109B, NOAA Twin Otter). Both miniature IRS and GPS systems present attractive options as a substantial number of airborne geoscience research projects move towards smaller and more cost efficient aircraft.

In this paper we discuss preliminary results from a test flight in which aircraft attitude was determined independently from a Litton 92 Laser Ring Gyro "strap down" IRS, a Trimble Advanced Navigation Sensor (TANS) Vector GPS system, and a conically scanning laser altimeter, the NASA Airborne Topographic Mapping (ATM) Lidar. During the conference, we will present results from an additional flight in which the TANS system was replaced by an Ashtech Attitude Determination Unit (ADU) GPS.

2. DATA

The data discussed herein were collected on Nov 5, 1999 on board the NOAA Twin Otter research aircraft (<http://www.oma.noaa.gov/aoc/>). The Twin Otter is particularly well suited for attitude determination by GPS. The aircraft is a high wing twin turbo-prop with struts connected from each wing to the bottom of the fuselage. This makes the wing extremely stiff virtually eliminating structural flexure from the attitude solution. Additionally, the high wing minimizes aircraft structures as a source of multi-path noise and signal errors.

For this test flight, the Twin Otter was based out of the NOAA Aircraft Operations Center in Tampa, FL. The flight took place over calm waters in Tampa Bay and the Gulf of Mexico. A flight track is shown in Fig. 1.

2.1 IRS Attitude Determination

The system used in this experiment was a Litton 92 "strap down" laser ring gyro without an integrated GPS. A laser ring gyro utilizes two counter rotating lasers to determine the absolute rotation of the gyro. The rotation is determined by examining differences in the path length over which the light travels. With a laser ring gyro IRS,

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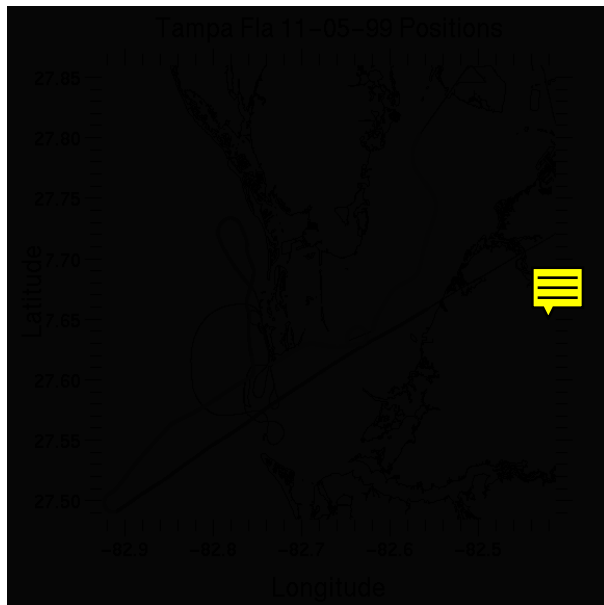


Figure 1 Flight track from flight of NOAA Twin Otter on 05 November, 1999. The thick lines indicate analysis times when the aircraft was over water and the ATM was operational.

attitude angles are then determined through the numerical computation from the gyro data and precision accelerometers within the IRS. The pitch and roll data are output digitally 64 times per second via an ARINC-429 serial data stream. The heading data are output in the same data stream, but at the lower rate of 32 Hz. The attitude data has a least significant bit of 0.02197° (14 bits in 360°).

2.2 GPS/TANS Attitude Determination

The Trimble Advanced Navigation Sensor (TANS) Vector system utilizes an array of four antennae and a system of four GPS receivers operating from a common clock, to provide the three-axis orientation of a platform. The angles are determined through the calculation of a 'most-likely' solution based on the carrier phase relationship of the "Course Acquisition (C/A) code" carrier signal from each of six satellites. Differences in carrier phase from a given satellite received at the four antennae are a result of the same signal arriving at each antenna with a different propagation time from the satellite. The differences in propagation times correspond to range differences and depend on the configuration of the antenna array relative to satellite position. The TANS Vector system then computes the attitude based on these range differences.

The accuracy of the system increases with increasing distance between the antennas (baseline). The primary baseline then determines

the accuracy for that particular measurement. The baseline for the fore and aft antenna determine the accuracy for pitch. The baseline for the two wing mounted antennae determine the accuracy for roll. For a baseline of 4 m, the accuracy is 0.07 degrees (RMS), according to manufacturer's specifications.

The TANS vector provides attitude measurements up to 10 times per second. The data are time-tagged with a GPS time stamp and made available through an RS-232 interface a few milliseconds after each measurement is completed.

Calibration of the system consists of a one-time survey of the relative antennae positions. The attitude of the aircraft during the calibration period is not known so the computed attitude from the TANS will tend to be biased. But the antenna coordinates and attitude biases are constants and are easily accounted for in processing. After the survey is complete the TANS will provide angles on 'cold-startup' typically within 1 to 2 minutes.

Like the IRS, the TANS Vector system is also prone to errors from a variety of sources. The most common error source is multi-path due to signal reflections/scattering, which can introduce phase errors as well as degrade signal strength, with corresponding reductions in solution accuracy. Signal strength is crucial for the TANS system and low SNRs typically lead to a 'no solution'.

2.3 ATM Attitude Determination

When operated over land the ATM provides a digital elevation map of the surface. But, when operated over relatively calm water, the ATM can provide a highly accurate, independent estimate of aircraft pitch and roll due to the water surface being very nearly tangent to the earth ellipsoid (differing only due to the effects of winds and local deflections of the gravity vertical, both quite small compared to the desired attitude accuracy).

The ATM scans a laser range finder in a conical pattern, ± 15 degrees from nadir, 20 times each second. The aircraft is virtually sitting on the pointed end of a cone with the larger end of the cone on the surface. The surface of the cone is composed of hundreds of precision laser range measurements between the platform and the surface. If the platform is level, the fore, aft, left and right range measurements will be the same. If the platform is rolling to the left, then the left range measurements are shorter than the right range measurements. If the platform is pitched up, the forward range measurements are longer than the aft ones. Using this as a model, the platform attitude is computed from a family of ATM range

measurements made during a single conical scan. Each ATM range measurement is accurate to approximately 5 cm. Given a flat surface and small waves, the accuracy of the ATM is greater than that of the IRS and GPS attitude estimates.

3. RESULTS

Attitude data from the three instruments were available at different rates. To facilitate direct comparison it was often necessary to either interpolate data to higher rates or low-pass filter and re-sample at lower frequencies. In the case of interpolation, a simple linear scheme was used. This has the potential of leading to small errors, but as we will see in the spectral data, this is generally not a problem.

The IRS is normally aligned with the aircraft frame at system installation and then uses local vertical for mission calibration. Subsequently, the system experiences small drifts in attitude angles. The ATM requires calibration relative to the IRS to account for the orientation of the ATM scan mirror. This calibration is done over water and/or surveyed runways/ramps and is a part of normal ATM data processing. The bias in the TANS data is 1 degree for roll and -1 degree for pitch. The data were adjusted to account for this bias.

3.1 Measurement Uncertainty

Data collected with the aircraft stationary, before flight, indicates uncertainties in the IRS angles of roughly 0.02 degrees for pitch and roll. From the TANS, the uncertainties are slightly greater, 0.05 degrees. Both of these numbers agree with manufacturers specifications for the given instrument.

3.2 Absolute Differences

Several 100 s blocks of data were chosen to compare mean squared differences between roll and pitch from the three instruments. Care was taken to choose data from segments both when the plane was performing maneuvers and during near-level flight. The RMS differences for the roll from the ATM and the IRS (Table 1) vary between 0.019 and 0.154. For the ATM and TANS, the differences are from 0.033 to 0.135. The RMS differences are less for the pitch data. For the ATM and the IRS, RMS differences are between 0.06 and 0.061, for the TANS, between 0.049 and 0.086. For the roll data, the RMS differences are comparable between the IRS and TANS. The differences for the IRS pitch are about 50% less than the differences for the TANS pitch.

Table 1 RMS differences for attitude angles between (a) ATM and IRS and (b) ATM and TANS for six 100-s blocks.

(a) roll	(a) pitch	(b) roll	(b) pitch
0.019	0.006	0.052	0.049
0.123	0.032	0.098	0.053
0.073	0.021	0.033	0.062
0.154	0.061	0.135	0.086
0.045	0.037	0.047	0.076
0.102	0.029	0.048	0.076

3.3 Timing Issues

Timing errors are evaluated by taking the cross correlation over a series of lags and looking for the lag at which the peak occurs. The data are first interpolated to 50 Hz. Cross-correlation as a function of lag (time) between the laser ATM roll and the IRS roll reveal a maxima at around 40 ms. This occurs at time scales *shorter* than the sample frequency for both the ATM and the TANS. Further analysis reveals differences between ATM and IRS (but not the ATM and TANS) angles with varying lags. In all instances, for the ATM-IRS comparison of pitch and roll, the difference was smallest when the IRS data were shifted by 0.04 to 0.06 seconds. Fig 2 shows plots of the cross correlation and relative error as a function of time lag. This analysis suggests that there exists a time lag in the IRS data. From comparisons between the ATM and the lower rate TANS data, no such lags are evident. Pitch, roll, and heading from the IRS each reveal different lag values.

3.4 Direct Comparison

Direct comparisons of measurements between the IRS (and TANS) and the ATM for a 150 s block are shown in Fig 3. Figs 3b and 3c show difference in pitch between the ATM and IRS. In 3b the IRS data are not shifted, but in 3c the data are shifted by 40 ms. It is apparent that the time shift greatly reduces the error associated with the pitch from the IRS. These results are consistent with those from ATM calibrations over ramps and water which typically show the best agreement between ATM and IRS data when the IRS time tags are shifted by 50 msec (\pm a few msec). Larger excursions (such as those at time 90 s) are due to missing data from the ATM.

Fig 3d shows differences for the ATM and

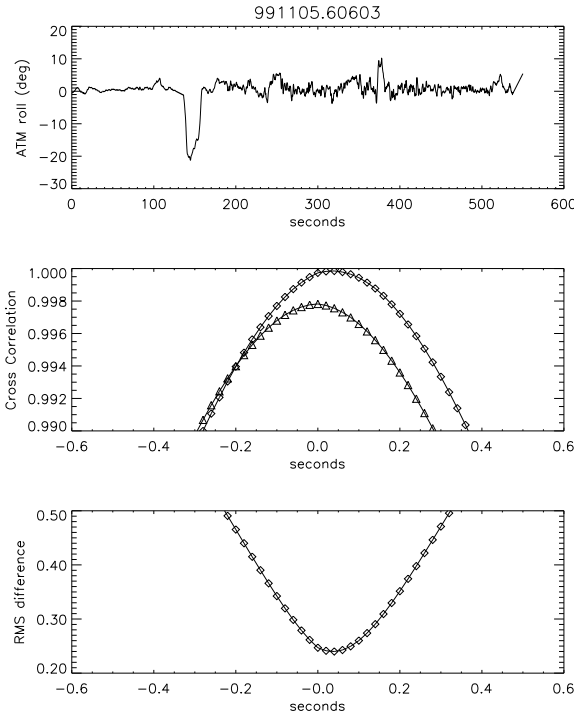


Figure 2 Analysis of lag time for attitude angles from the IRS and TANS. The top plot shows the roll from the ATM laser for the time period of the analysis. The middle plot shows the cross correlation between ATM and IRS roll (diamonds) and ATM and TANS roll (triangles). The lower plot is the root-total-square (RTS) difference from the ATM and IRS roll as a function of time shift for the IRS.

TANS pitch for the same data segment. The error in the TANS angles is roughly ± 0.1 degree, an order of magnitude larger than for the IRS. Note, also, that there appears to be a low frequency component to the error suggesting that the relative error at higher frequencies may be better than 0.1 degrees.

3.5 Frequency Response

Spectra calculated from roll data from all three devices are shown in Fig 4. All spectra agree remarkably well for frequencies below 2 Hz. Above 2 Hz, the spectra from the TANS (4a) begins to 'roll up'. This is likely due to contamination due to noise. It was shown earlier that the error in angles is greater for the TANS than for the other two instruments.

The spectra for the ATM and IRS agree remarkably well for low frequencies extending to 10 Hz (the Nyquist frequency for the ATM). Beyond 10 Hz, the IRS spectra indicate increased power. It is not clear from this data whether these peaks are real or are due to some type of noise contamination.

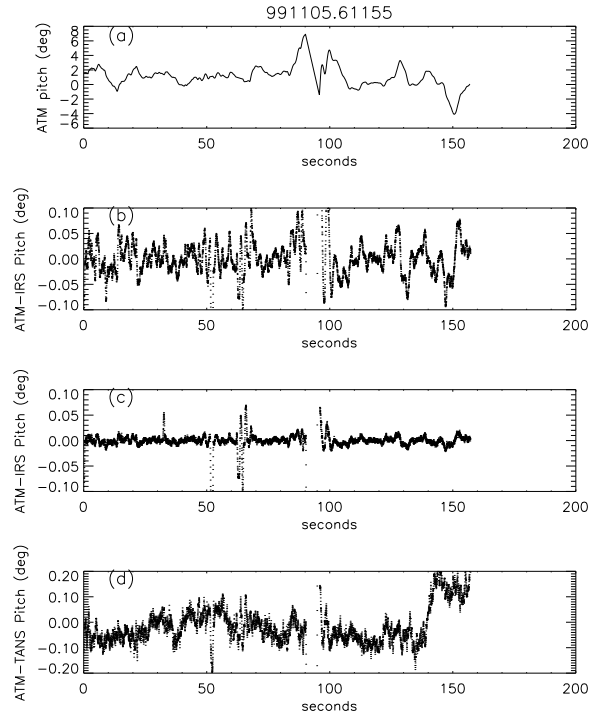


Figure 3 150 second data block showing pitch from ATM laser. Plots (b) and (c) show difference between ATM and IRS pitch for (b) no time lag and © 0.04 second lag for the IRS. Plot (d) shows difference between ATM and TANS pitch for the same period.

4. DISCUSSION

The measured errors for angles from both the TANS and IRS are within the manufacturer's specifications. For the TANS, there appears to be a low frequency component to the error suggesting the solution may 'wander' over several seconds. It is likely that this wander is due to multi-path effects on the GPS receiver phase measurements. Higher frequency components, however, appear to have a higher degree of accuracy, relative to the low frequency wander. Unfortunately, one is not able to realize the increased accuracy, as it is not possible to remove or reduce the 'wander' error. More rapid fluctuations in the TANS attitude error occur over a few seconds (see Fig 3C at 140 s). Typically, such changes do not correspond to changes in platform orientation. It is possible that such fluctuations are the result of the receiver changing from one satellite signal to another. Further investigation is needed to support this conjecture.

The spectra for all three devices agree remarkably well, indicating all seem to have sufficient frequency response for their respective

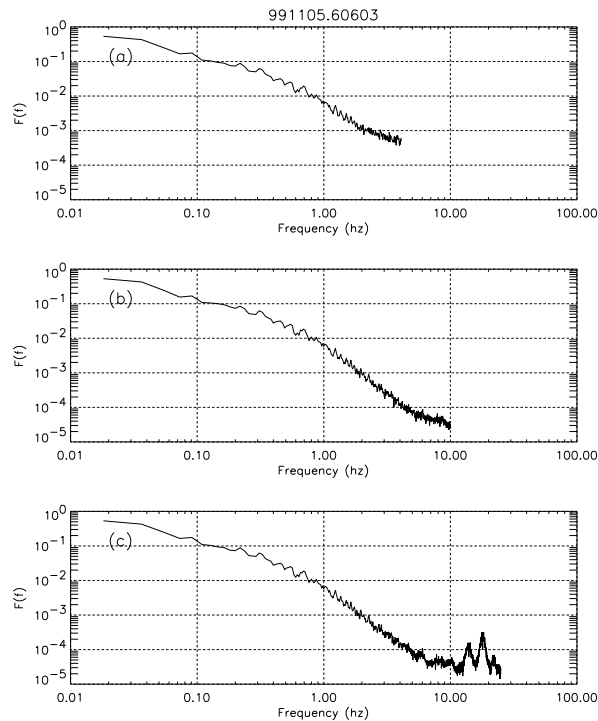


Figure 4 Power spectra as a function of frequency for the same period as that shown in Fig 2. The three plots correspond to the (a) TANS, (b) ATM, and (c) IRS.

sampling rate. The spectra from the TANS begin to roll up at 2 Hz. Such behavior is indicative of noise, either due to the inability of the instrument to respond at those frequencies or its inability to resolve fluctuations at that level. The TANS spectra levels off between 2 and 5 Hz, with a power of 8×10^{-4} . The total variance for this portion is then 0.0024 deg corresponding to a standard deviation of roughly 0.05 deg. This of course suggests that fluctuations above roughly 2 Hz in these data are simply too small for the TANS to detect.

Spectra from the IRS reveal two interesting peaks, one near 15 Hz and another near 20 Hz. It is not apparent whether these peaks are real or artifacts, although it is possible that the IRS is detecting real vibrations. Unfortunately, the ATM data do not extend out to this frequency, so at this point, all is conjecture.

Lastly, a time lag is evident in the IRS data, with a magnitude comparable to that which has previously been observed in comparisons of ATM and IRS data. No lag is evident in data from the TANS.

5. CONCLUDING REMARKS

The work presented herein represents a

preliminary analysis of data from one flight. Further analysis of this data set will be forthcoming. In addition, a more in-depth analysis of the frequency response of the TANS would be beneficial. A method to extend GPS attitude data to higher frequencies utilizing relatively inexpensive accelerometers is currently being used on small atmospheric research aircraft (Crawford and Dobosy, 1997). A full understanding of the accuracy of such methods requires the type of analysis described herein perhaps augmented with data from a GPS-accelerometer system.

6. REFERENCES

- Trimble Navigation, 1994: TANS Vector GPS Attitude Determination System: Specification and User's Manual. Trimble Navigation Limited, Sunnyvale, CA .
- Crawford, T. L., and R. J. Dobosy, 1997: Pieces to a puzzle: Air-surface exchange and climate. *GPS World*, **8**, 32-39.